EPFL

CIVIL-309: URBAN THERMODYNAMICS

Prof. Dolaana Khovalyg

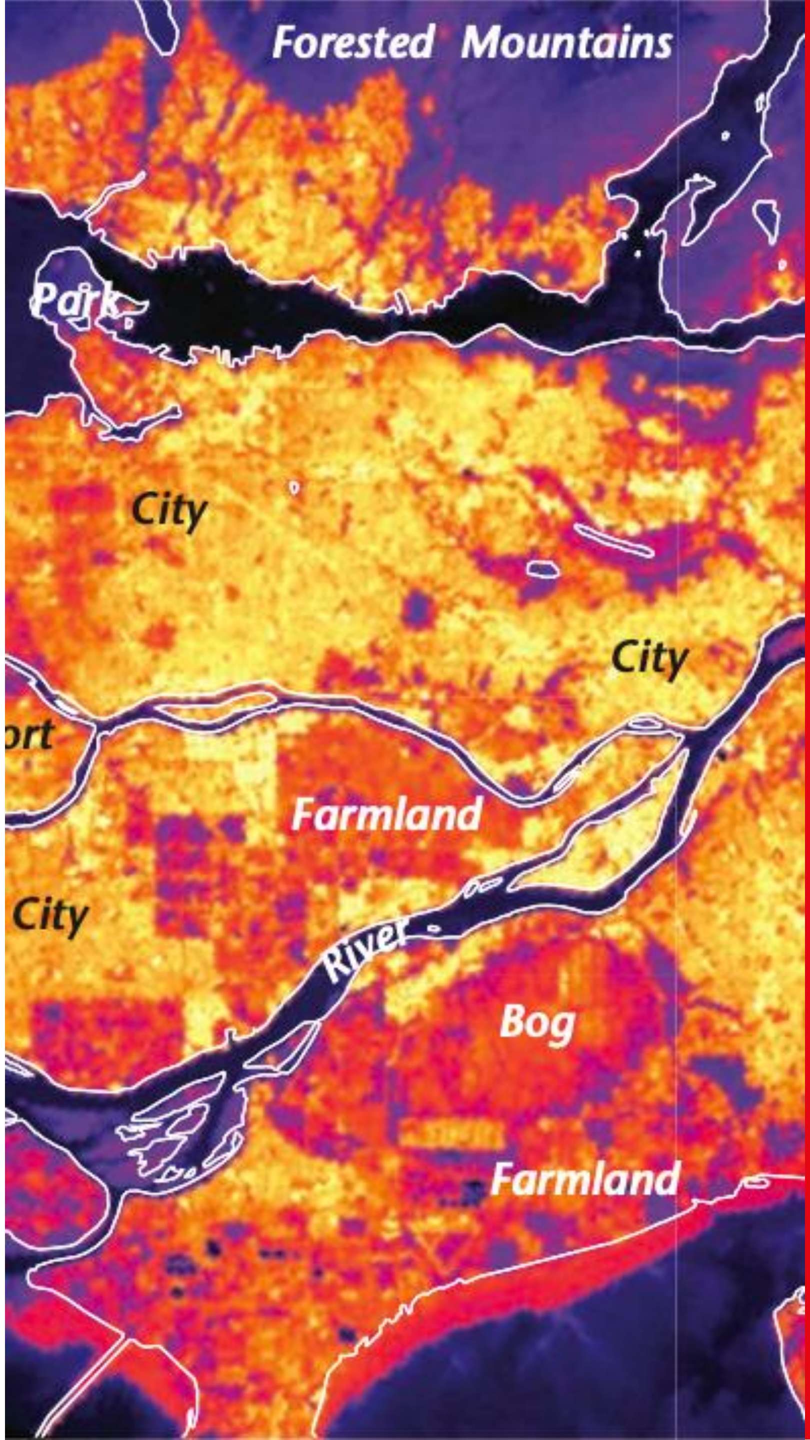
Lecture 02:

Overview of physical parameters

19 September 2025

Course Schedule

Week	Date	Time	Topics	Instructor
1	12.09	2 x 45'	**Course overview:** content, evaluation, topics **Urban characteristics, Urban Heat Island (UHI) effect**	DK
		1 x 45'	Introduction to the web tool **CityTherm** (part I)	DK
2	19.09	1 x 45'	**Overview of physical parameters**	DK
		1 x 45'	**Introduction to the course project I**	DK, JY
		1 x 45'	Supervised work on the course project I	JY
3	26.09	2 x 45'	**Heat Transfer: Conduction and radiation**	DK
		1 x 45'	Supervised work on the course project I	JY
4	03.10	2 x 45'	**Heat Transfer: Convection and evaporation**	DK
		1 x 45'	Supervised work on the course project I	JY
5	10.10	1 x 45'	**Campus walk:** exploring urban thermodynamics	DK, JY
		2 x 45'	Supervised work on the course project I	JY
6	17.10	3 x 45'	Supervised work on the course project I **Course project I submission deadline: 16:00 on October 17**	JY
7	24.10		**BREAK**	



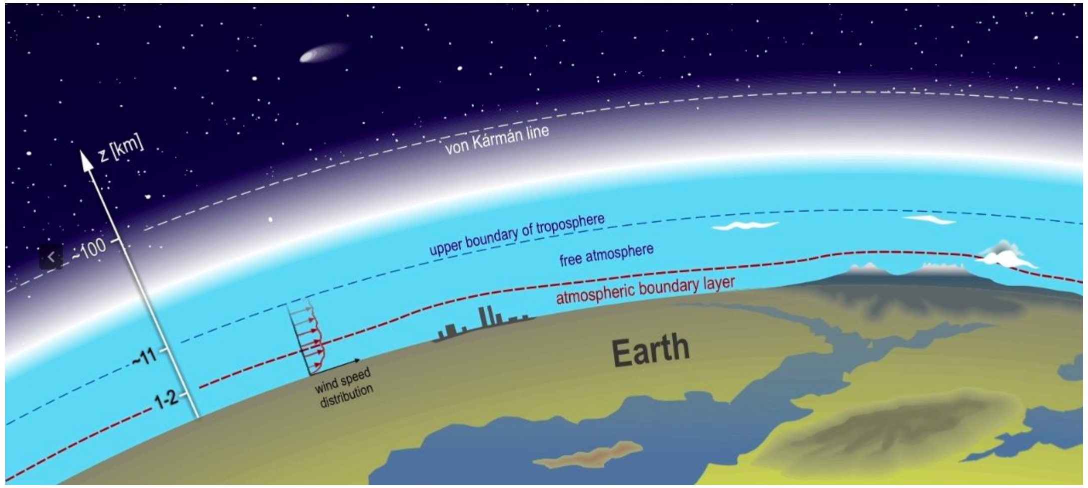
CONTENT:

I. **Urban meteorology**
- Structure of urban atmosphere
- Micrometeorology
- Winds speed and precipitation

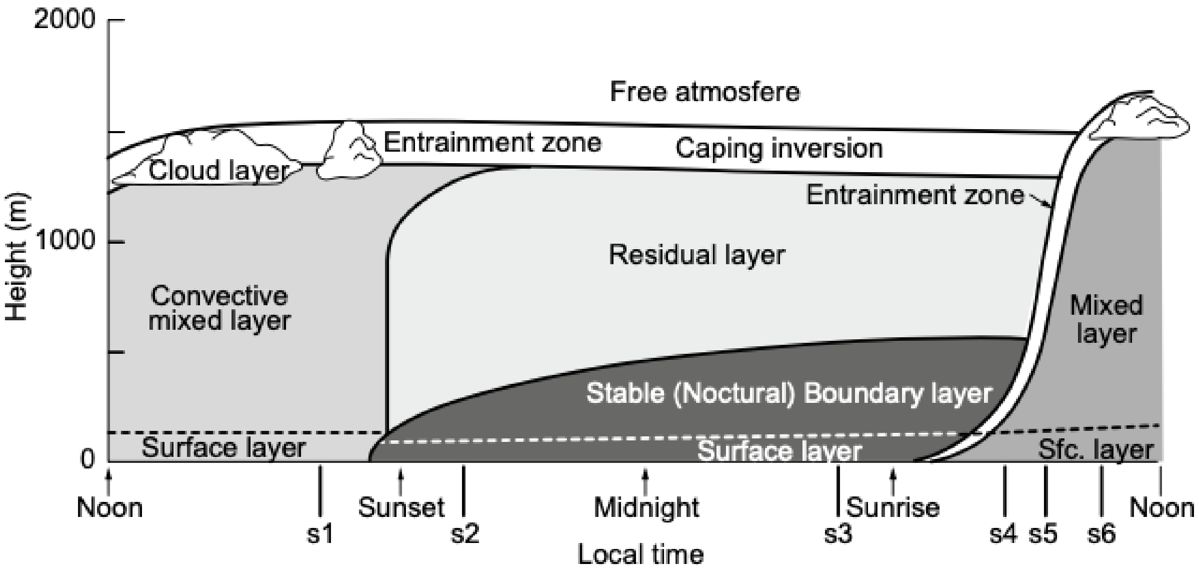
II. **Physical parameters**
- Temperatures (air, surface, ground)
- Atmospheric pressure
- Water vapor, moist air, air humidity

Urban atmosphere: Atmospheric boundary layer

- **Troposphere:** the lowest layer of the *atmosphere*, it constitutes 80% of its mass.
- **Atmospheric boundary layer (ABL):** lowest layer of the *troposphere*. It is directly *influenced by Earth's surface perturbations*. It stretches 1-2 km, above is the **free atmosphere**.
- The *height* and the *structure* of the **atmospheric boundary layer (ABL)** *vary* between *day and night.*
- The atmospheric boundary layer *above urban areas* is called the **urban boundary layer (UBL)**.
- The **urban boundary layer (UBL)** is *higher* than the **rural boundary layer (RBL)** because the *interactions* between the *Earth* and its *atmosphere* are *stronger.*



Source: https://bmeafl.com/the-project-proposal/



Source: Rodrigues, Fundamental Principles of Environmental Physics, p.2

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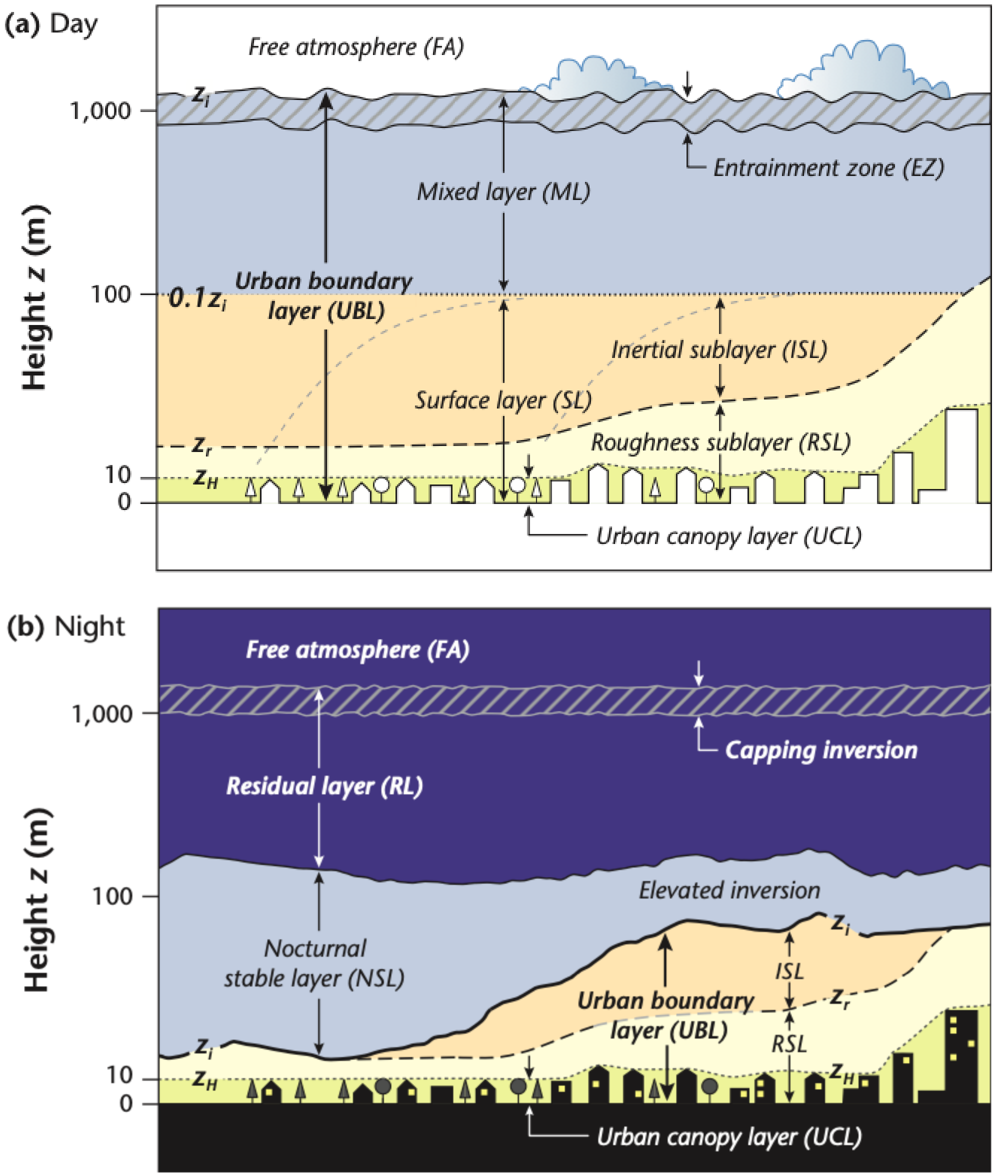
Urban atmosphere: Atmospheric boundary layer

- The **urban boundary layer** is composed of *two* layers:
  - **Surface layer** (lower 10%)
  - **Mixed layer** (upper 90%)

- **Surface layer**: a layer with *heat* and *mass exchanges* between the Earth and its atmosphere. It is composed of 2 layers:
  - **Roughness sublayer (RSL)** - *lower part* affected by individuals elements, it is turbulent and 3D.
  - **Inertial sublayer (ISL)** - the *upper part* affected by assembles of individual elements, it varies mainly in the horizontal direction.

- **Mixed layer:** heat and mass exchange are *dampened* by turbulent motion; temperature, water vapor, wind speed are almost *uniform* with height



Source: Oke, Urban Climates, p.31

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Urban atmosphere: Wind speed

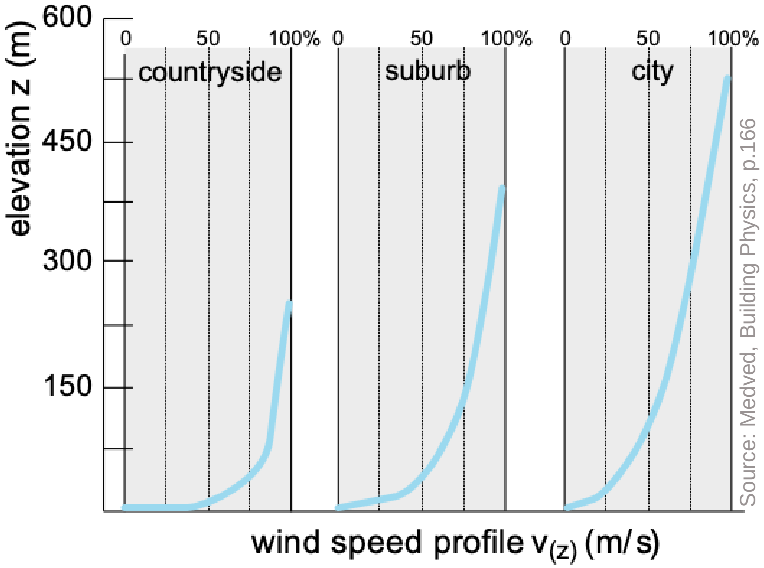
- **Wind speed at the surface** is **zero** and ***increases* exponentially** *with the height*:

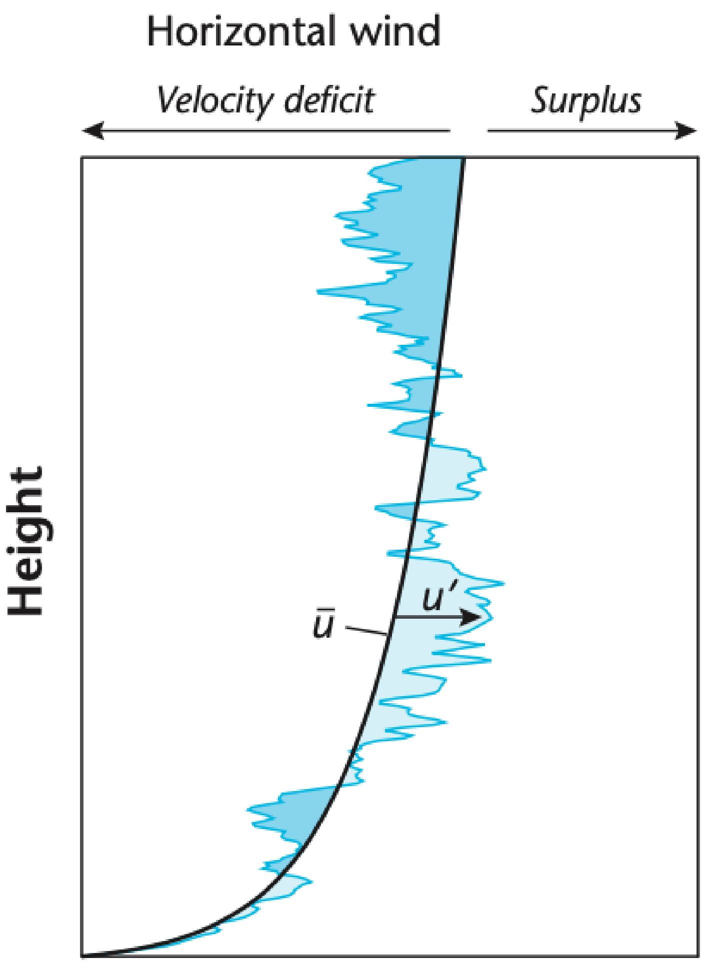
$$u(z) = \left(\frac{z}{z_r}\right)^{\alpha} \cdot u(z_r) \qquad (2\text{-}1)$$

z_r - reference height
α - surface roughness coefficient or Hellmann exponent

- In urban areas, wind speeds are *lower* at *lower heights* because of the **surface roughness** effect

Surface type	Surface roughness
Water body	0.10
Meadow	0.13
Forest	0.20
Settlement	0.25
City with tall buildings	0.31





Source: Oke, Urban Climates, p.100

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Urban atmosphere: Urban roughness

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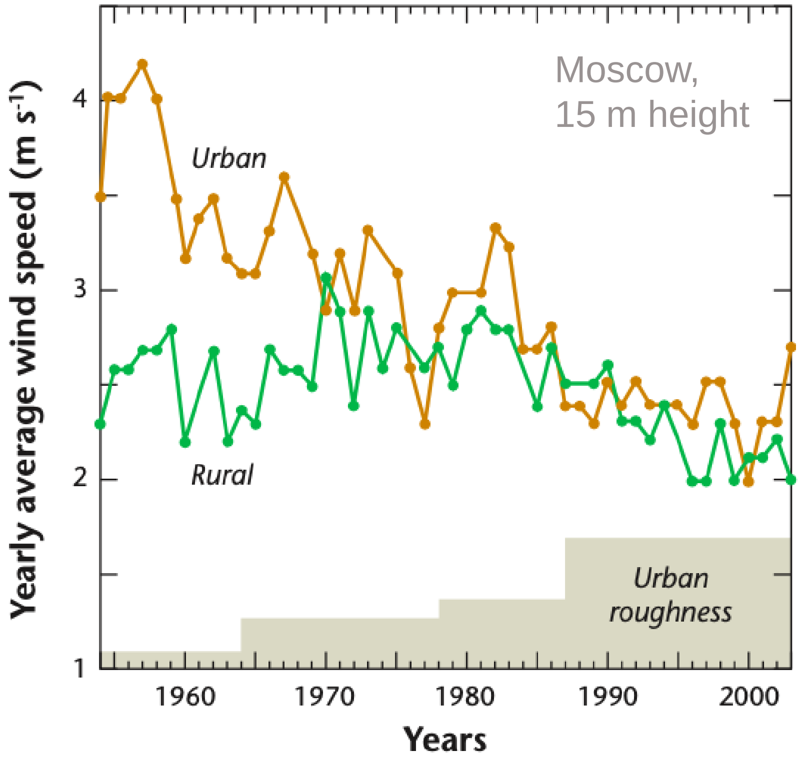
- **Urban roughness** is characterized by:
  - The **mean height of roughness elements** z_H
  - The **roughness length** z_0
  - The **Hellmann exponent** α
- **Roughness length z_0**: height at which the wind speed theoretically becomes *zero* in *the absence of wind-slowing obstacles*.
- Two approaches to estimate the *roughness parameters*:
  - **Micrometeorological approach:** in-situ measurements of wind to solve the equation of the atmospheric boundary layer profile.
  - **Morphometric approach:** computing the roughness parameters from the dimensions of the urban elements.



Source: Oke, Urban Climates, p. 101

Source: Oke, Urban Climates, p. 103

Local climate zone type	Mean height of roughness elements z_H (m)	Roughness length z_0 (m)	Hellmann exponent α
Lawn	0.2 – 0.5	0.03 – 0.06	0.11 – 0.13
Compact low-rise	5 – 8	0.3 – 0.8	0.2 – 0.25
Compact mid-rise	7 – 14	0.7 – 1.5	0.23 – 0.27
Compact high-rise	11 – 20	0.8 – 2	0.26 – 0.29
High-rise	> 20	> 2	0.29 – 0.35

Urban meteorology: Micrometeorology

- **Meteorology** – **science** dealing with the **atmosphere** and **its phenomena** (varies on the *spatial*- and *time*- scale).
  - Spatial scales: *micro, meso, synoptic, global*
- **Micrometeorology** is applied at the ***local* scale.** It studies *small-scale* (< 1km) *atmospheric processes*, associated with the short-term (< 1h) *interaction* of the atmosphere and the Earth's surface.
- **Micrometeorology considers:**
  - *Turbulence phenomena* present at space scales of a few meters
  - *Surface transport* and *energy exchange*
  - *Heat* and *humidity* at the ground layer of the atmosphere

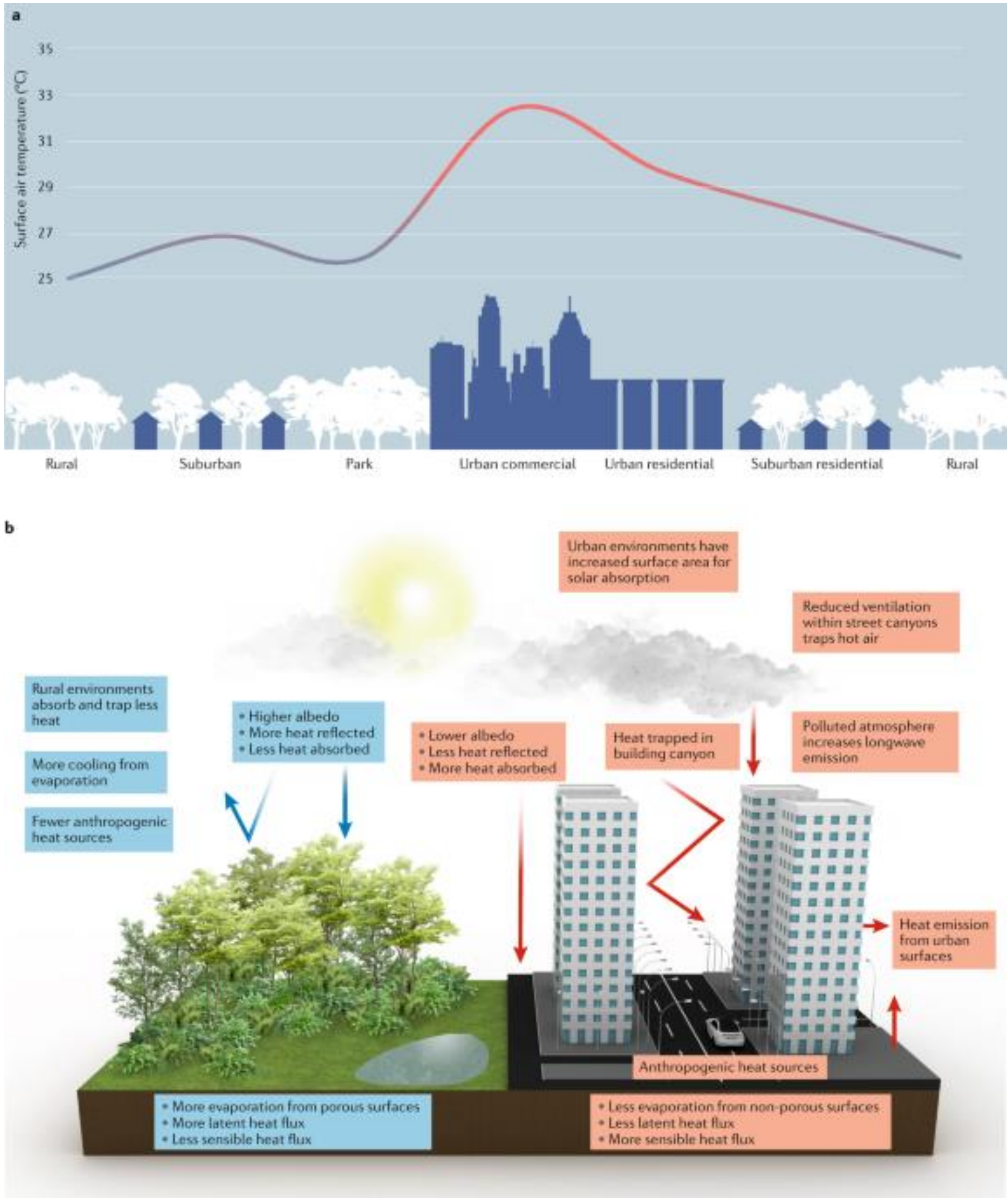


Image from: https://www.nature.com/articles/s43017-020-00129-5

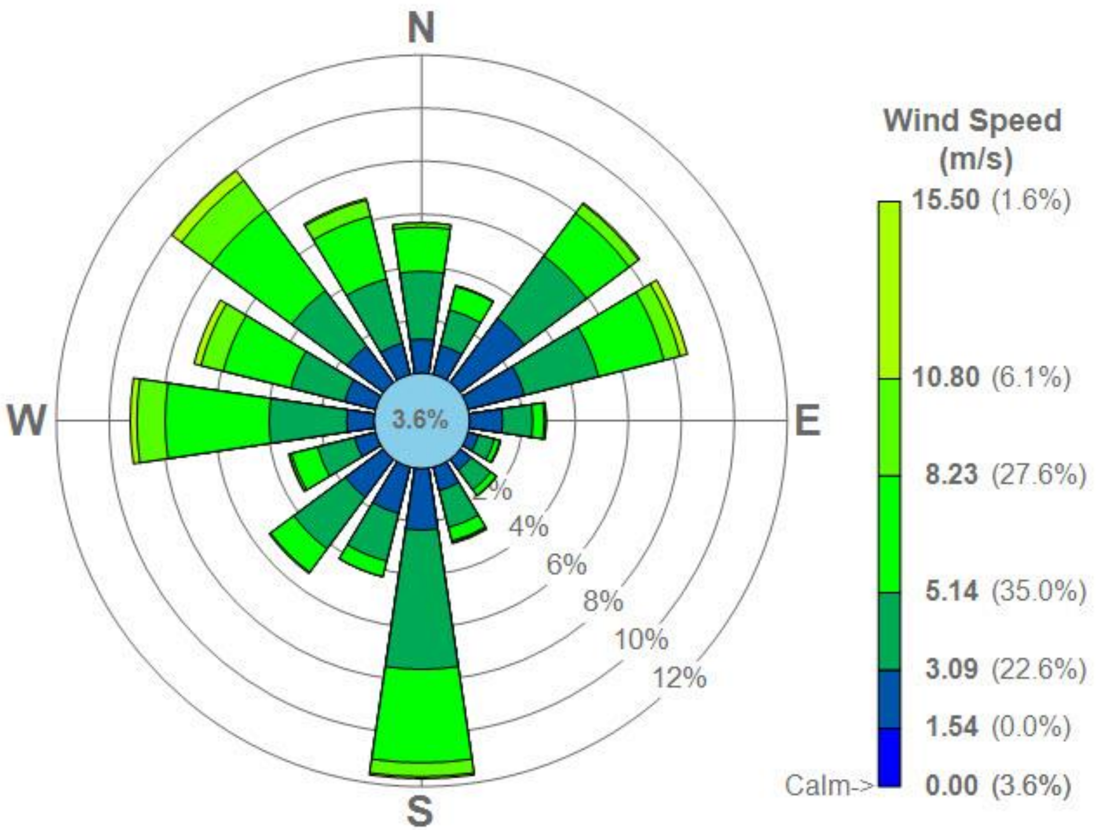
Urban meteorology: Wind speed and direction

- **Wind** is driven by a **pressure difference in the air** due **to different air density**. It describes the *movement of air.*
- **Wind speed** or **magnitude** $\bar{u}$ $(\frac{m}{s})$ is the resultant norm of the wind components $\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{w}$ in the main direction

$$\bar{u} = \sqrt{u(x)^2 + v(y)^2 + w(z)^2}$$

- The **wind** *above the urban canopy* is considered to be **two-dimensional**
- **Wind rose - a graphical representation of the *repartition* of the wind speeds according to the wind direction**. It gives *statistical information* on the wind direction and allows to determine the *predominant* wind speeds
    - The wind direction is typically shown between 0 and 360° (North = 0°, East = 90°, South = 180°, West = 270°)

La Guardia Airport, New York, 2008



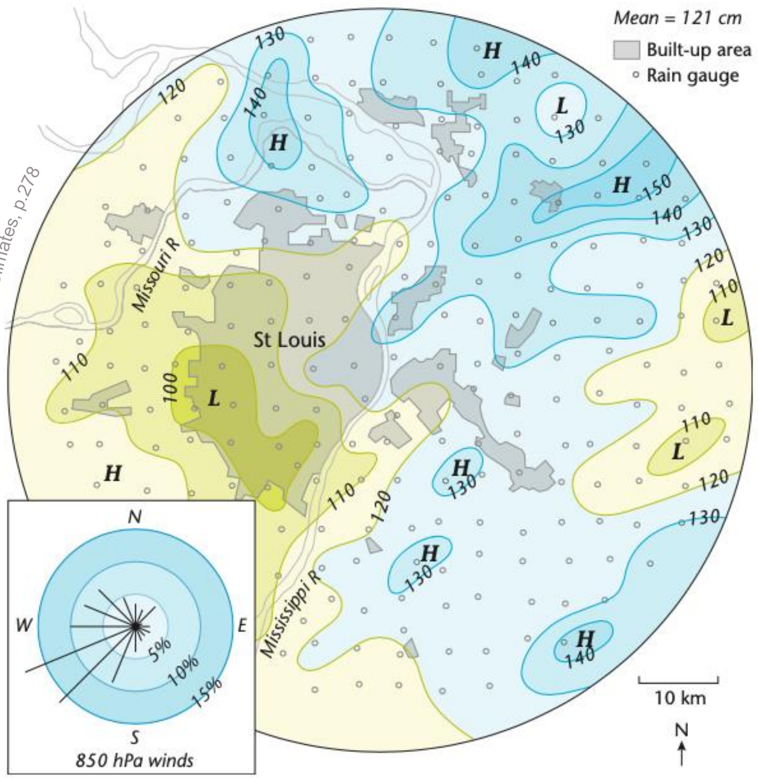
Source: https://en.wikipedia.org/wiki/Wind_rose

Wind animation in real time:

[Weather Maps | Live Satellite & Weather Radar - meteoblue]

Urban meteorology: Precipitation

- **Precipitation**: **amount of rainfall on the ground** whether in the form of **water drops**, **snow flakes**, or **droplets of mists**
- It is expressed in *water depth*, *snow water* or *equivalent of snow thickness* **in mm**
- Precipitation is characterized by its **intensity** and its **occurrence**.
- **Precipitation intensity** is expressed in $\frac{mm}{h}$
- Precipitation is *higher* in *some* urban areas because cloud condensation is *stimulated* by the presence of air pollutants, the urban boundary layer structure and the presence of the urban heat island.

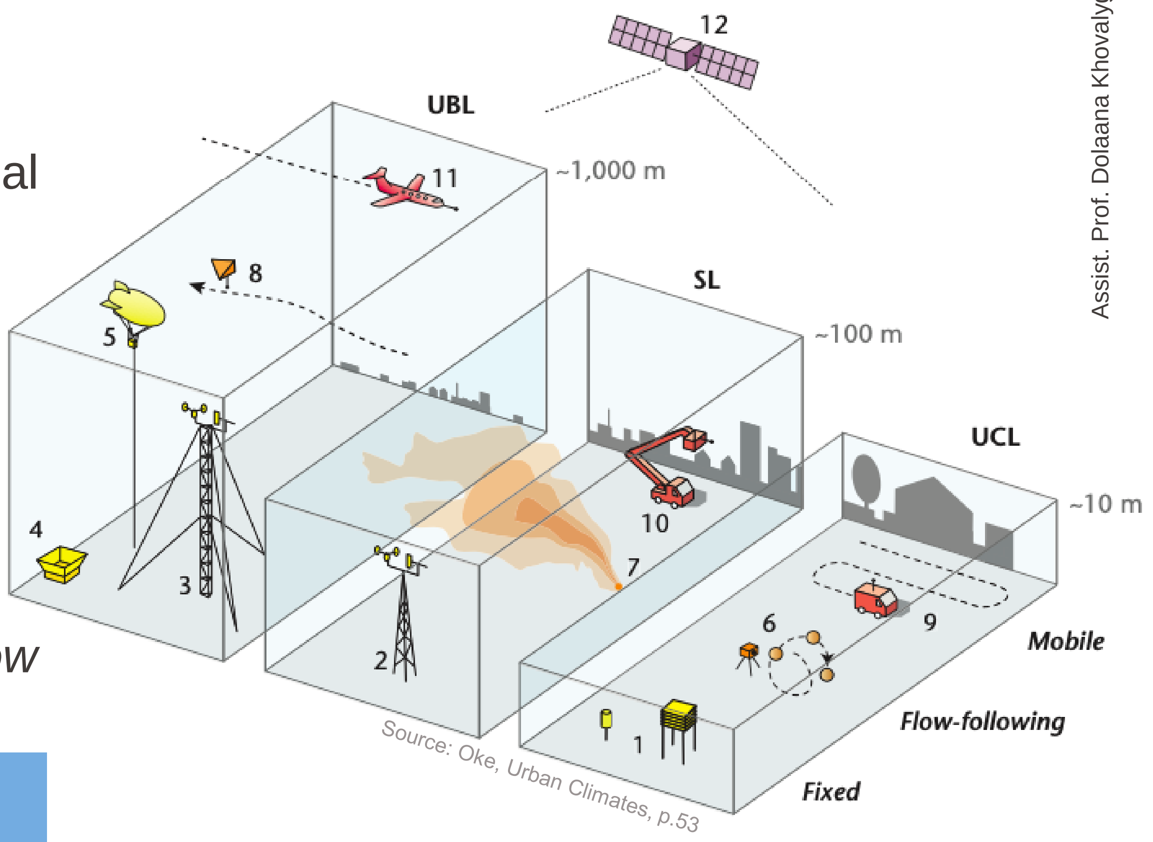


Source: Oke, Urban Climates, p.278

Characterization of the rain	Intensity of precipitation ($\frac{mm}{h}$)
Very weak	< 0.25
Weak	0.25 – 1.0
Moderate	1.0 – 4.0
Heavy	4.0 – 16.0
Very heavy	16.0 – 50.0
Extreme	> 50.0

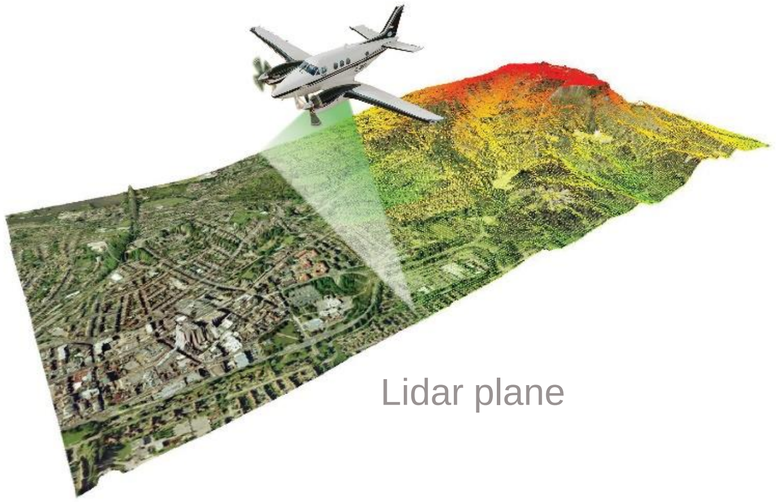
Urban meteorology: Measurements

- Two types of measurements:
  - **Long-term routine** urban meteorological information (e.g., weather forecast)
  - **Field campaigns** (e.g., to answer specific research questions)
- They can use sensors that are used
  - **In situ**
  - Remotely (**remote** sensors)
- … and that can be *fixed, mobile* or *following the flow*



Ground-based, aerial and remote-sensing platforms

1. Stevenson screen
2. Meteorological tower
3. Tall tower
4. Ground-base sensing platform
5. Tehered ballon with intruments winched up and down
6. Small-scaled ballon traced by camera
7. Tracer release experiment
8. Tetroon ballon
9. Vehicle
10. Mobile crane platform
11. Helicopter, airplane and drone
12. Satellite remote-sensing



Lidar plane

Portative weather station

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Urban meteorology: Solar Irradiance Measurements

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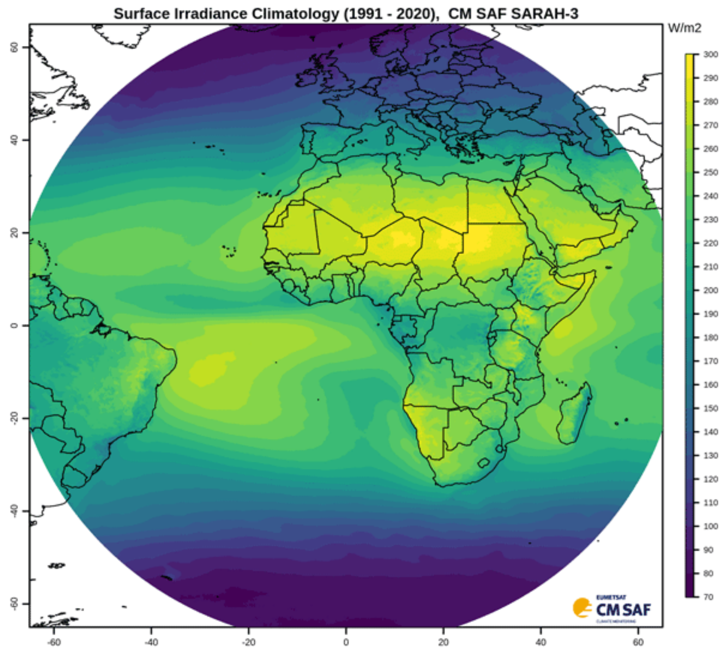
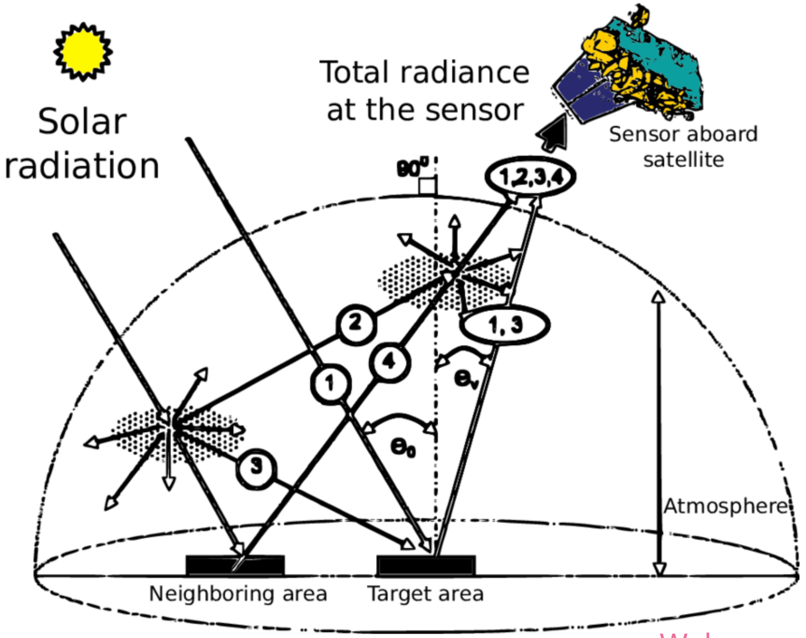
- Measurements using **satellites**:
  - Large spatial cover
  - Uniform datasets across regions
  - Low accuracy at local scale
  - Large spatial resolution

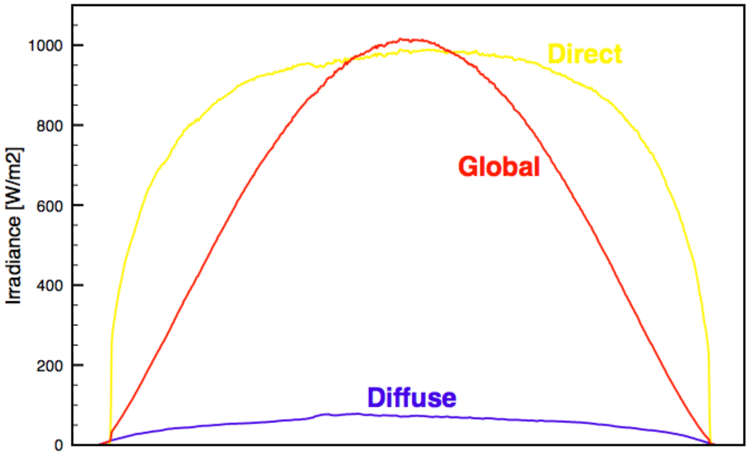


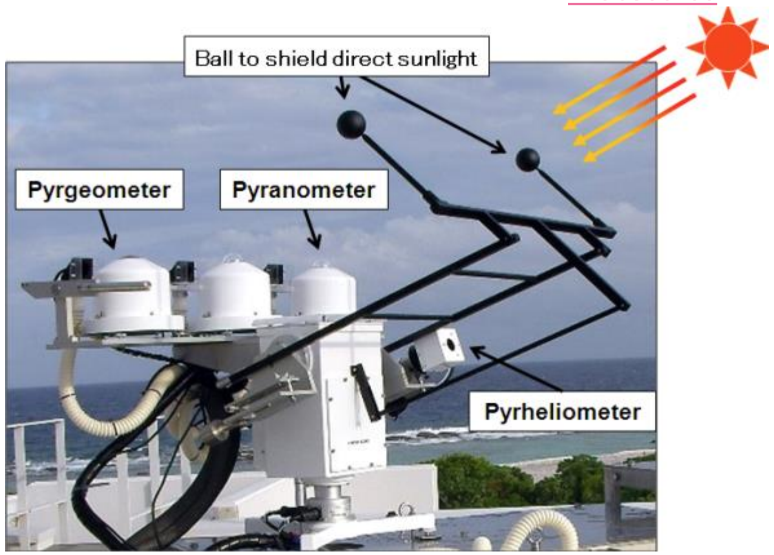
https://essd.copernicus.org/articles/16/5243/2024/



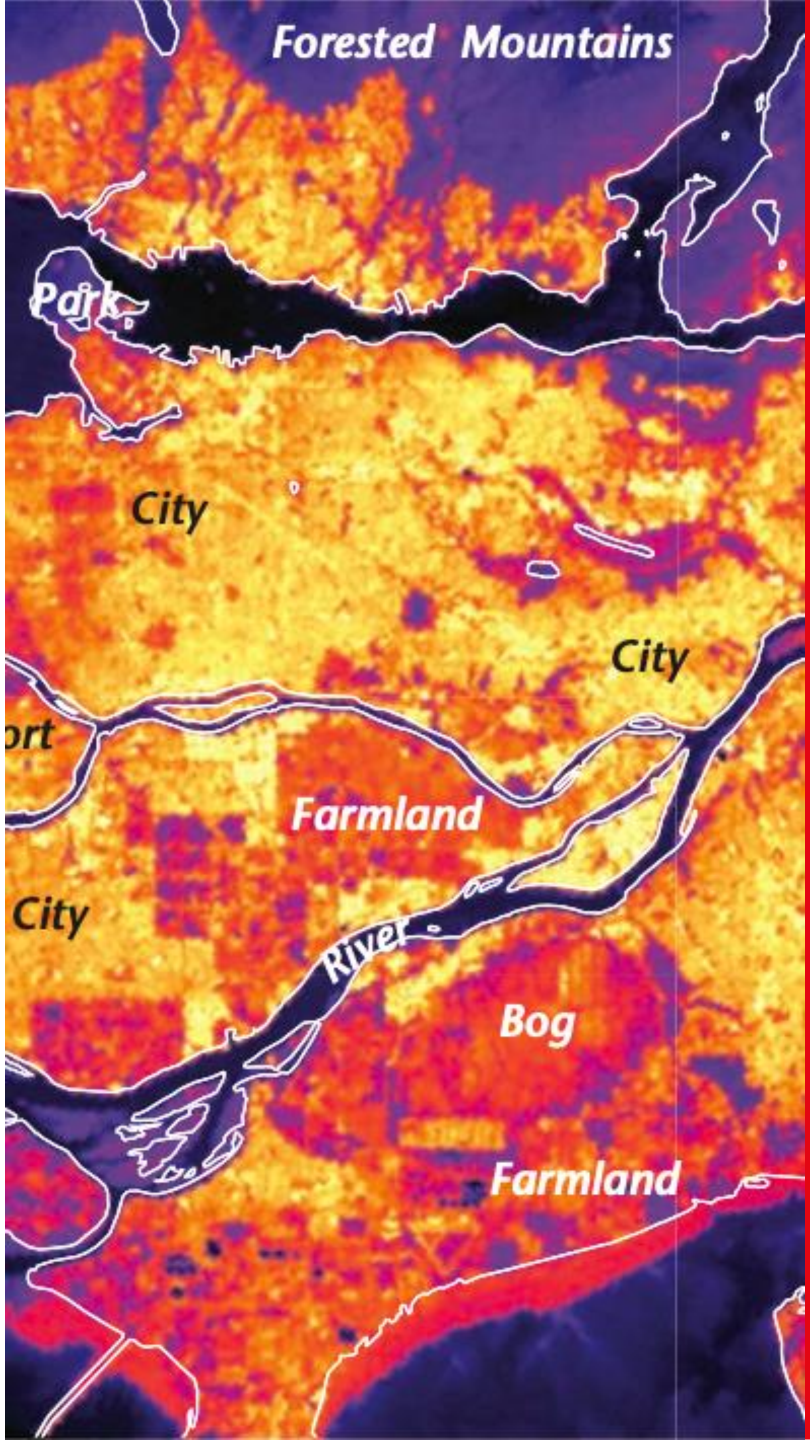
[Websource]

- Measurements with **ground-mounted pyranometers**:
  - High accuracy
  - Captures local microclimate
  - Limited spatial coverage





https://www.jma-net.go.jp/kousou/obs_third_div/rad/rad_sol-e.html



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Overview of Air Temperatures

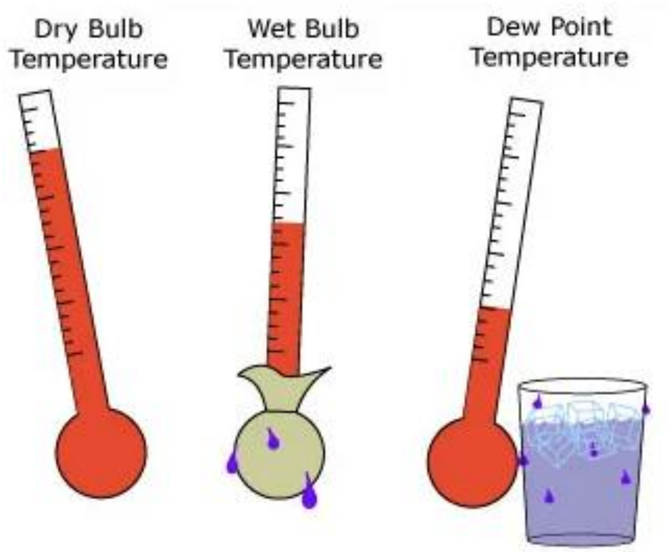
- **Dry bulb temperature T_{db}** (K or °C): the **air property** that is most commonly used.

  By referring to "**air temperature**", we normally refer to **dry bulb temperature** affected by the *moisture* present in the air.

- **Dewpoint temperature T_d** (K or °C): the temperature the air needs *to be cooled* to (at constant pressure) in order to achieve *a relative humidity* of 100%.

- **Wet bulb temperature T_{wb}** (K or °C): the *lowest* temperature that can be reached under given ambient conditions *by the evaporation of water only*.

  Theoretical limit to human survival for more than a few hours is a wet-bulb temperature of 35°C.

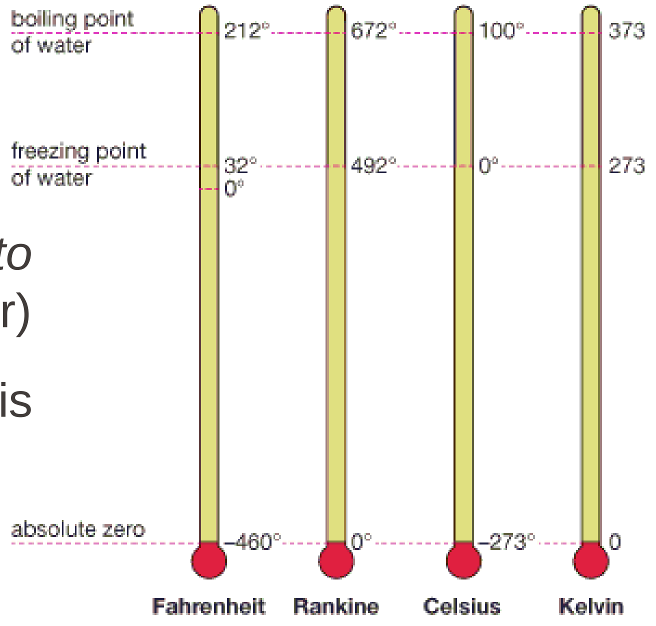


- **Temperature scales:** measurement of temperature *relative to* easily reproducible states (e.g., *freezing* and *boiling* points of water)

- **Kelvin scale** – *thermodynamic (absolute) temperature scale* that is independent of properties of any substance or substances

$$0°C = 273.15\ K$$

* Important to pay attention when the absolute temperature in [K] is used



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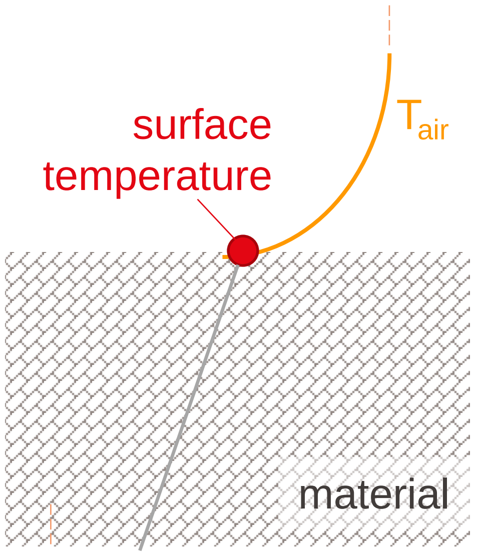
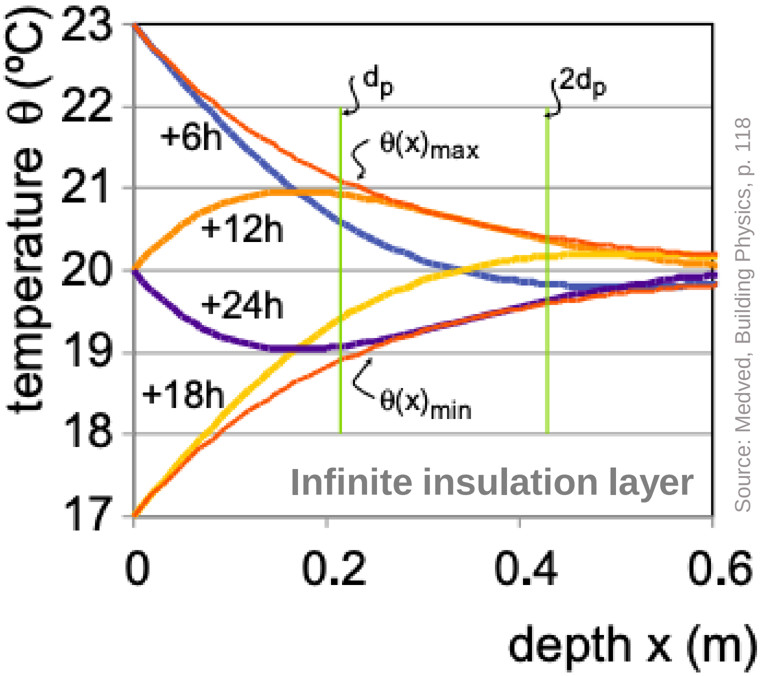
Surface temperature

- **Surface temperature T_s** (K or °C): **temperature** of a **material** (artificial matter) **at its outer limit**, at its surface *in contact* with another solid, liquid or gas.
  - Surface temperature is determined with **the surface energy balance**
  - It depends of the **temperature** of *materials in contact* and the *solar radiation* reaching the surface.
  - It follows a *daily* and *seasonal* variation delayed with respect to the *variation of solar variation*.
- **Dynamics of surface temperature:**
  - **Maximum surface temperature** is reached *1-2 hours after maximum solar radiation* and **minimum temperature -** *1-2 hours before the first direct sunlight*.
  - The **amplitude of the variation** depends on the *material's properties.*
  - **Temperature** on *the air side of the surface* **varies exponentially.** Air temperature could have 20 K difference over 1 mm next to a heated surface.





Source: Medved, Building Physics, p. 118

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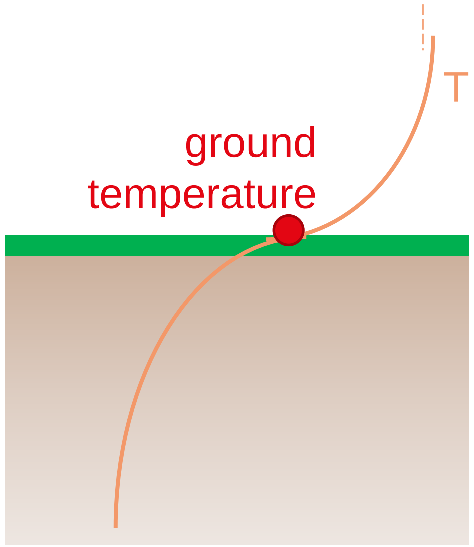
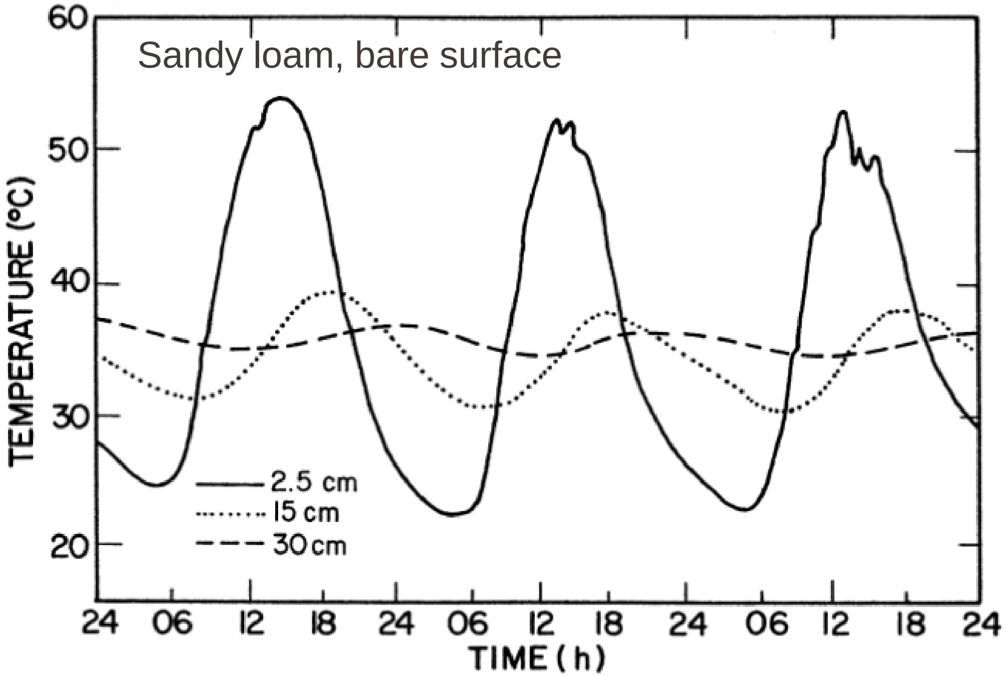
Ground/Land temperature

- **Ground temperature next to the surface** is *affected by the physical processes* of the **upper environment**
- Major difference **between ground** and **other material** temperature: only the *outer surface temperature changes* while the *bottom temperature remains constant* after a certain depth (the thickness of ground is considered infinite)
  - Ground temperature next to the surface *varies daily* and *with season* with *time lag* depend on *solar radiation* and *air temperature*
  - The **ground thermal properties** and **deep temperature** depend on *soil composition* and *structure*

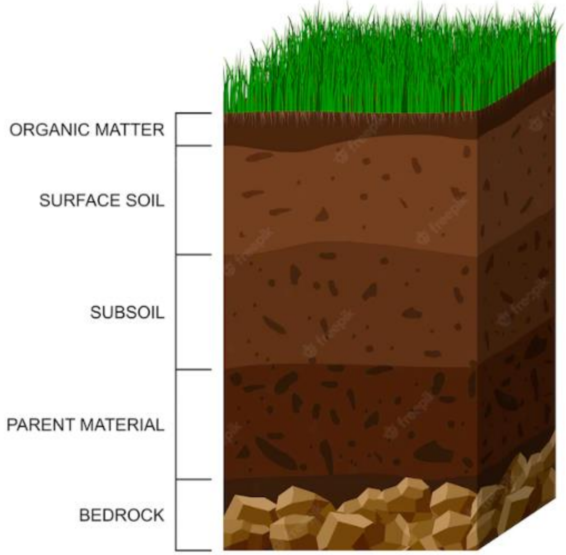




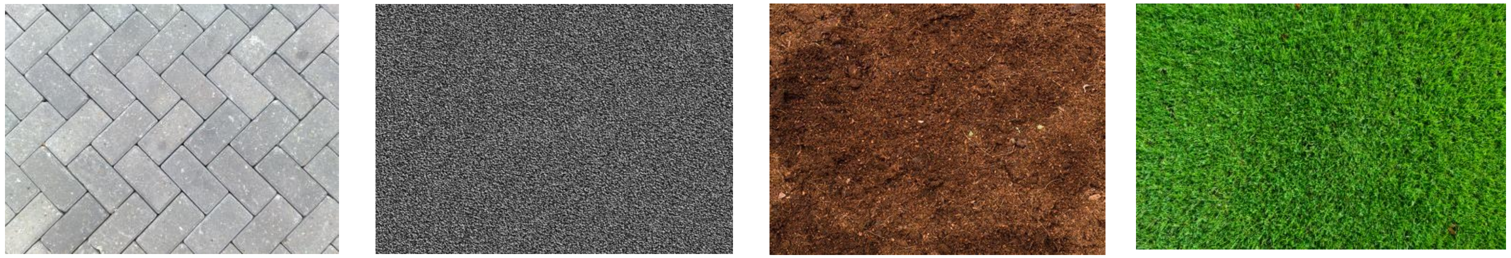
Source: Arya, Introduction to micrometeorology, p. 48

Ground vs. Soil

- **Ground** is the **surface of the Earth**. Ground is used indifferently to describes the *surface* and the *volume* of matter below it (i.e. soil).
- **Soil** is **a mixture of organic matter**, **minerals**, **gases**, **liquids** and **organisms**. Soil is *a three-state system* composed of solids, liquids and gases. It is usually *structured into layers* of different composition.
- Ground surfaces can be:
  - **Artificial**: pavement
  - **Natural**: bare soil or soil with vegetation



Picture from: web link



Soil

Ground

Picture from: web link

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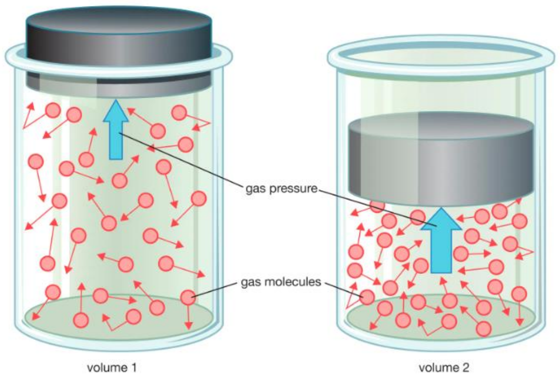
Atmospheric pressure

- **Atmospheric pressure** p_a $(Pa = \frac{N}{m^2})$: **weight** *exerted by* **the overhead atmosphere** on **a unit area of surface**

$$p_a = \frac{V_a \cdot \rho_a \cdot g}{A} \quad (2\text{-}2)$$

$$1\ bar = 10^5\ Pa \quad (2\text{-}3)$$

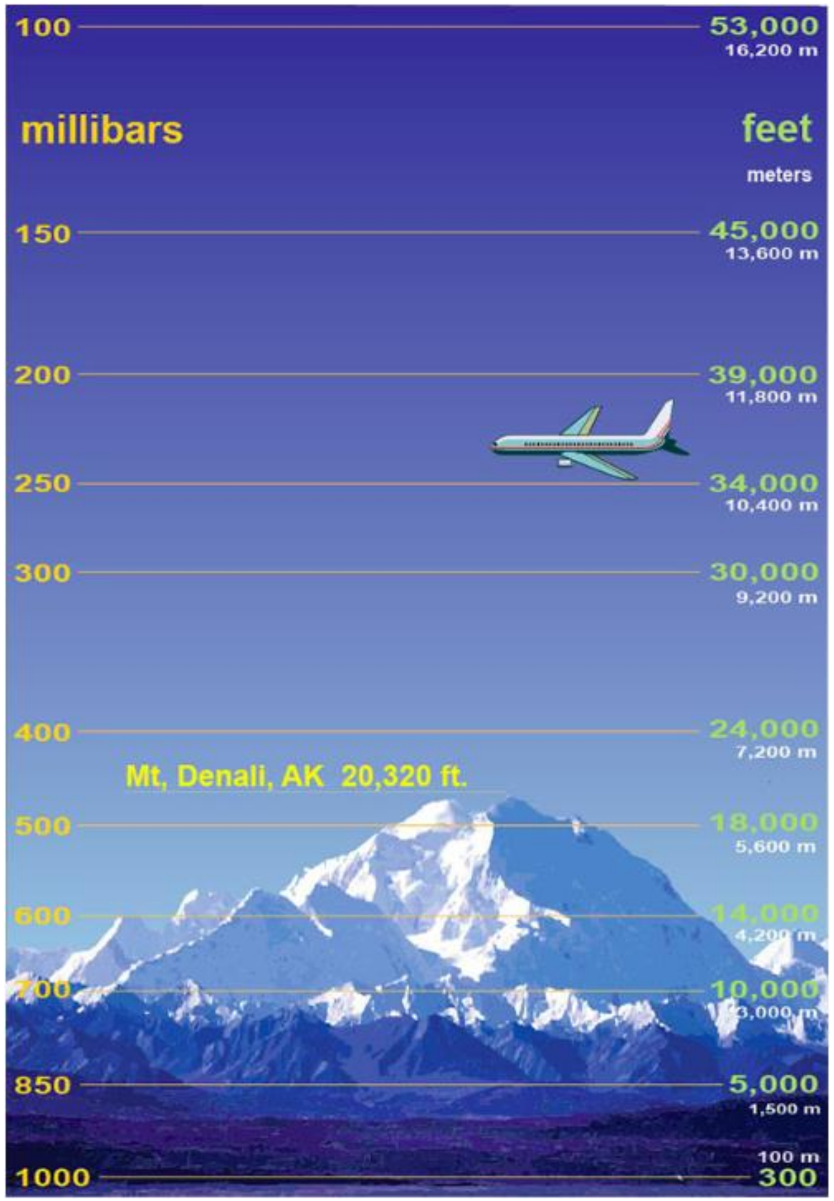


Source: https://www.britannica.com/science/pressure

- Air pressure decreases with the altitude (around 10 $\frac{Pa}{m}$)
- Pressure is exerted *equally in all directions*
- Air (dry) pressure is related to air density and temperature through **the Ideal Gas Law:**

$$p_a \cdot V_a = n \cdot R \cdot T \quad (2\text{-}4a) \longrightarrow p_a = \rho_a \cdot R_a \cdot T \quad (2\text{-}4b)$$

R_a - *specific gas constant* for dry air (287.04 $\frac{J}{kg \cdot K}$)



Source: https://www.weather.gov/jetstream/pressure

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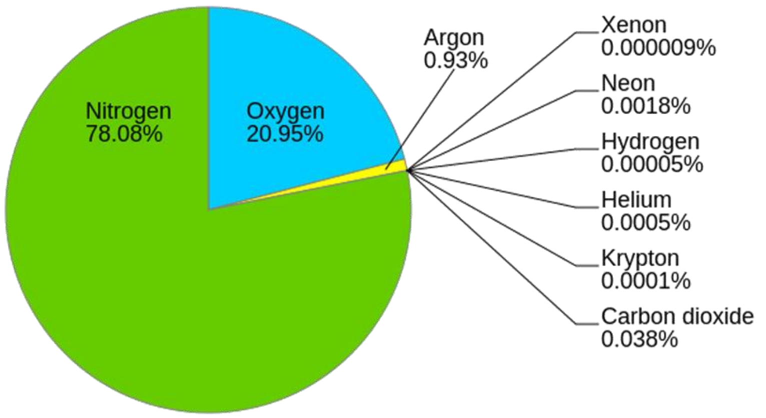
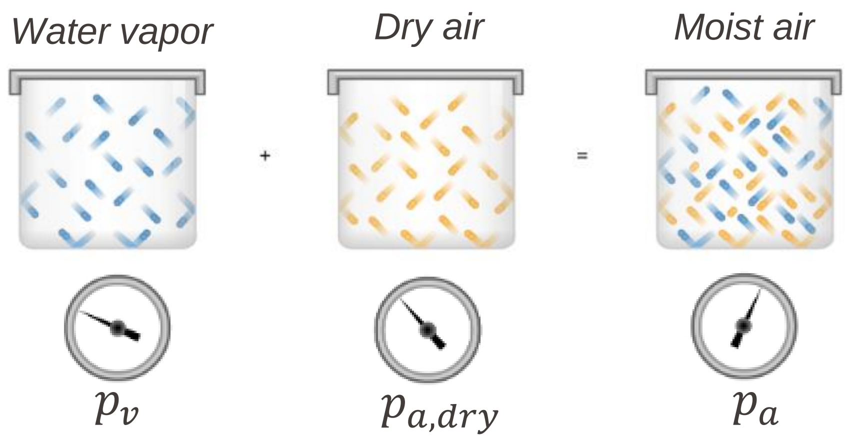
Water vapor

- **Standard air** or **barometric pressure** p_a 1013 mbar (=101.3 kPa) is defined *at sea level*
- Air is a mixture of gases, predominantly N_2, O_2, Ar, and CO_2. Important to consider that air *always* contains **water vapor**
- **Humidity** or **moisture** – the amount of **water vapor** *present* in the air



- **Partial pressure of water vapor** p_v (Pa): the pressure that would be exerted *by water vapor* if it occupied the same volume as the moist air on its own
  - **Partial pressure of water vapor** in the air p_v is between 0.1-12 kPa, depending on air temperature and humidity



- Moist air behaves according to **the Dalton's law** – the *total air pressure* p_a is equal to *the sum of the partial pressure* p_i of the i-th gas present in the air (i.e., $p_{a,dry}$), and *the partial pressure of water vapor* p_v.

$$p_a = \sum_i p_i + p_v = p_{a,dry} + p_v \quad (2\text{-}5)$$

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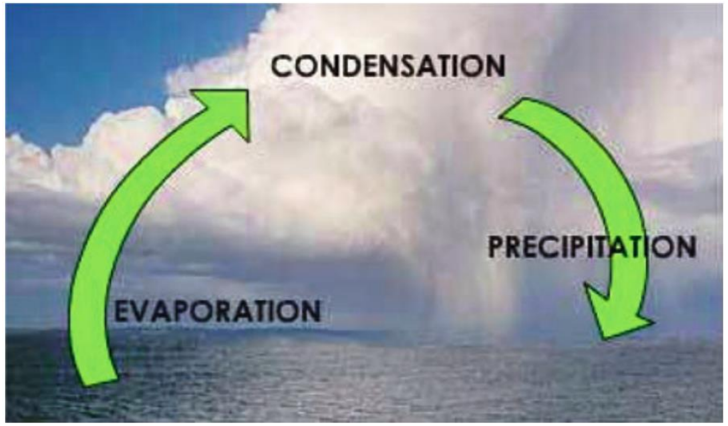
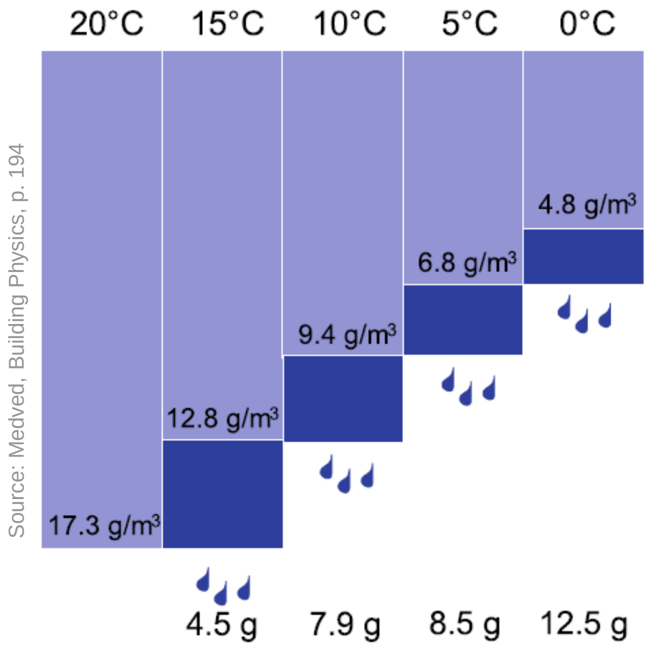
Moist air

- **Source of humidity:** evaporation process from surfaces:
  - An <u>increase</u> in moisture caused by **evaporation**
  - A <u>decrease</u> in moisture caused by **condensation**
- Depending on the *moisture ratio* between the air and the surface and their respective *temperatures*, **evaporation** or **condensation** happens
- Air is **saturated with water vapor** when *another water input* would lead to *condensation*
- A state of **saturation** is achieved *by moistening the air* (by evaporation from the water surfaces, by spraying the water droplets) or by cooling it to the saturation temperature (= dew point temperature T_{dew})
- **The water content** in the air is highly ***dependent on air temperature.*** Hot air can hold more water-vapor molecules than cold air due to the increase in **water-vapor saturation pressure** $p_{v,sat}$ with **an increasing air temperature**

Source: Spiridonov, Fundamentals of meteorology, p. 133





Quantity of liquid water condensing from 1m³ of saturated air as the air is cooled from 20ºC to lower dew point temperature

Psychrometric Properties: Moist Air

- **Water vapor saturation pressure $p_{v,sat}$ (Pa)** – the **pressure** at which **water vapour** is ***in thermodynamic equilibrium*** **with its *condensed state***.
  - At higher pressures ($p > p_{v,sat}$), water *condenses*
  - At lower pressures ($p < p_{v,sat}$), water *evaporates*
  - Relationship between $p_{v,sat}$ and T is approximated by *the Clausius-Clapeyron eqn*:

(2-6) $$p_{v,sat} \approx p_o \cdot e^{\frac{L}{R_v} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)}$$

R_v - water-vapor gas constant (461 $J/K \cdot kg$), T_o =273.15 K, p_o = 611 Pa, L – latent heat (2.5 · 10^6 J/kg for vaporization, and 2.83 · 10^6 J/kg for sublimation)

  - Simplified $p_{v,sat}$ (Pa) formulas (t - air temperature in °C):

For t > 0°C:

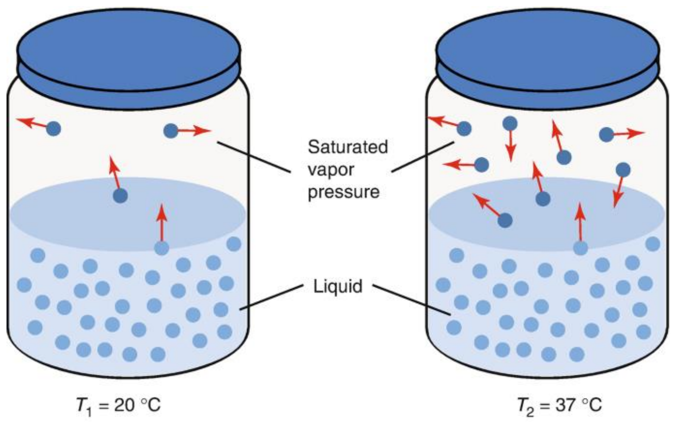
$$p_{v,sat} = 611 \cdot e^{\frac{17.08 \cdot t}{234.18+t}} \quad (2\text{-}6a)$$

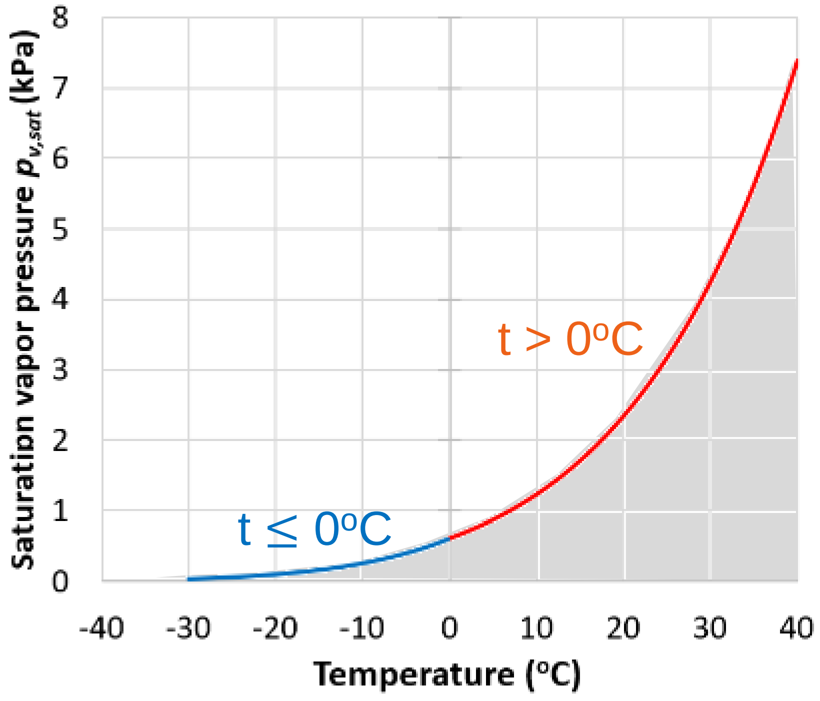
For t ≤ 0°C:

$$p_{v,sat} = 611 \cdot e^{\frac{22.44 \cdot t}{272.44+t}} \quad (2\text{-}6b)$$

- **Water vapor pressure deficit Δp_{vd}** (Pa) is defined as how much more partial pressure can be taken up before saturation occurs:

$$\Delta p_{vd} = p_{v,sat} - p_v \quad (2\text{-}7)$$





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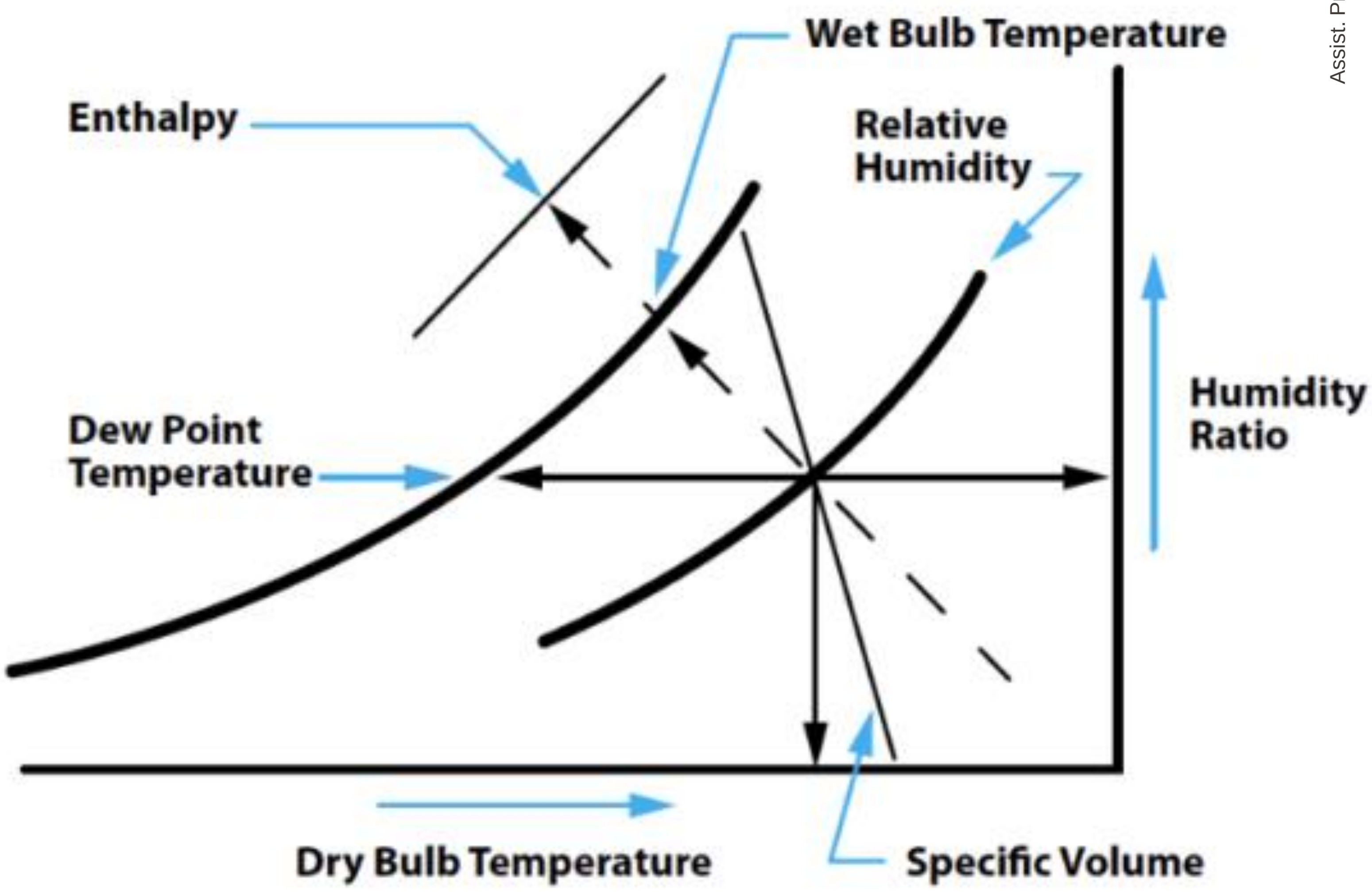
Psychrometric Properties: Moist Air

- **Psychrometric chart** presents *physical* and *thermal properties* of *moist air* in a graphical form (**at standard atm. pressure 101.3 kPa**)
- **Parameters displayed:**
  - Dry bulb temperature T_a
  - Wet bulb temperature $T_{wb,a}$
  - Dew point temperature T_{dew}
  - Specific enthalpy h_a (*internal energy of air measured relative to a reference temperature* 0 ºC)
  - Relative humidity φ or *RH*
  - Absolute humidity x
  - Vapor pressure p_v
- Absolute humidity ranges:
  - *in nature:* 2-20 g/kg
  - *indoor air:* 4-12 g/kg



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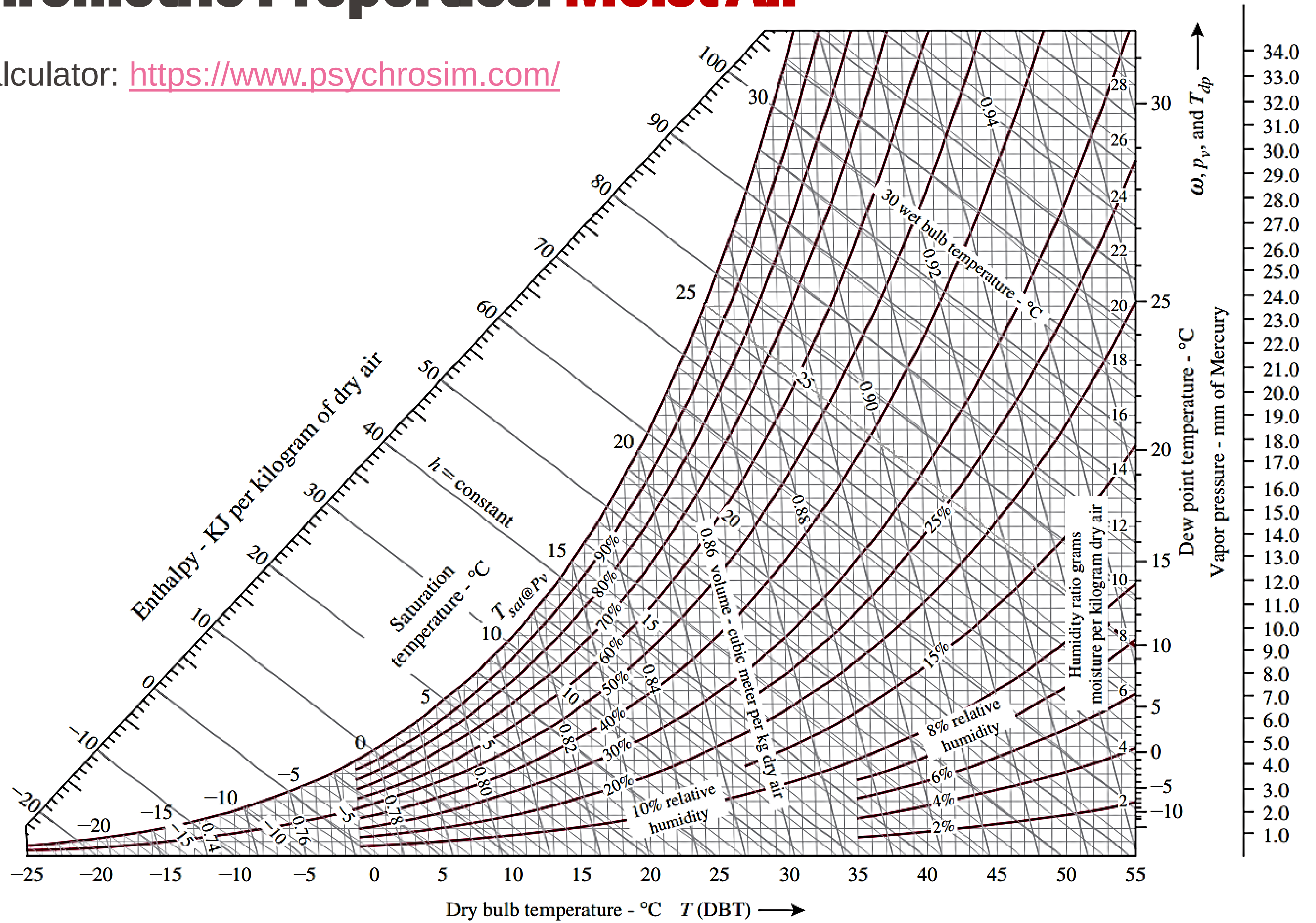
Psychrometric Properties: Moist Air

Online calculator: https://www.psychrosim.com/



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Psychrometric Properties: Air humidity

- **Specific humidity q ($\frac{kg}{kg}$)**: the **mass ratio** between **water vapour mass** and **the mass of moist air** (does not change with the change of temperature and pressure)

$$q = \frac{m_v}{m_a} \quad \text{(2-8a)}$$

$$q = \frac{p_v \cdot M_v / M_{a,dry}}{p_a - (1 - M_v/M_{a,dry}) \cdot p_v} = 0.622 \frac{p_v}{p_a - 0.378 \cdot p_v} \quad \text{(2-8b)}$$

- **Absolute humidity** or **humidity ratio x ($\frac{kg}{kg}$)**: **mass of water vapor** *per* **1 kg of dry air**

$$x = \frac{m_v}{m_{a,dry}} \quad \text{(2-9a)}$$

$$x = \frac{p_v \cdot M_v}{p_{a,dry} \cdot M_{a,dry}} = 0.622 \frac{p_v}{p_a - p_v} \quad \text{(2-9b)}$$

- **Relative air humidity φ (- or %)**: **ratio** of **the actual partial pressure of water vapour p_v** to the **water vapour saturation pressure $p_{v,sat}$** at *a specific air temperature* (often labeled as "RH", air is saturated at $\varphi = 1 \; or \; 100\%$)

$$\varphi = \frac{p_v}{p_{v,sat}} \text{ (-)} \quad \text{(2-10a)}$$

$$\varphi = \frac{p_v}{p_{v,sat}} \cdot 100 \text{ (\%)} \quad \text{(2-10b)}$$

- **Humidity by volume v ($\frac{kg}{m^3}$)**: **water vapour mass** per unit **volume of air**

$$v = \frac{p_v}{R_v \cdot (t + 273.15)} = \frac{p_{v,sat} \cdot \varphi}{462 \cdot (t + 273.15)} \quad \text{(2-11)}$$

- t – air temperature (^oC),
- M_v - molar mass of the water vapour (18 $kg/kmol$),
- $M_{a,dry}$ - molar mass of dry air (28.9 $kg/kmol$),
- R_v - gas constant of water vapor ($462 \; J/kg \cdot K$)

Thank you for your attention!

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